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A Study of Trends in Low-Energy Development Patterns in China: A Data-Driven Approach

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Abstract: China is currently undergoing a transition towards high-quality economic development, and the industrial structure is being optimized. However, there are still regional imbalances in economic development and energy consumption. Therefore, it is necessary to investigate whether the disparities in electricity intensity between provinces and industries can converge over time. This paper investigates the trend towards low-energy consumption in China and verifies the club convergence of electricity intensity across provinces and industries in China using a data-driven log *t*-test and club clustering algorithm. The study innovatively finds that the convergence of electricity intensity is more pronounced in the tertiary sector. The value added of electricity consumption in the tertiary sector is closely related to the level of regional economic development, further indicating that the pattern of low-energy development is closely related to factors such as the geographical location of the province, regional radiation capacity, and industrial structure. In order to accelerate low-energy development in China, the paper proposes policy recommendations related to low-energy development to improve the quality of China's economic development.

Keywords: electricity intensity; convergence analysis; secondary industry; tertiary industry

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1. Background and Introduction

A low-energy development pattern refers to the reduction of energy consumption in the process of economic development by means of, for example, the adoption of energy-saving technologies and the optimization of the energy structure. Thus, the aim is to reduce pollution of the environment and protect natural resources. The low-energy development pattern is an important part of sustainable development and an important way to address the challenges of climate change and energy security. The low-energy development pattern can reduce energy consumption and carbon emissions, reduce the risk of environmental pollution and climate change, while promoting economic development and social progress.

Electricity intensity refers to the amount of electricity consumed per unit of gross domestic product. It is an important indicator of the efficiency of energy use in a country or region. The main characteristic of a low-energy development pattern is to maintain economic growth while minimizing energy consumption and environmental pollution. Therefore, the convergence analysis of electricity intensity can reflect the current trend of the low-energy development pattern.

The convergence analysis of electricity intensity makes it possible to compare trends in the variation of electricity intensity between different regions over time. If the variation in electricity intensity between regions tends to decrease, this indicates that overall regional energy efficiency is gradually increasing, demonstrating a trend toward low-energy development in the region. People are becoming more efficient in the way they use energy, which is relatively less consumed, and electricity intensity is gradually decreasing. This trend indicates that the low-energy development pattern is gradually becoming the mainstream trend in social development. Conversely, if the electricity intensity shows a fluctuating or increasing trend between different regions, this indicates that the regional energy use efficiency still needs to be improved, and more energy-saving efforts are needed.

1.1. Overview of China's Industrial Structure

China has a strong industrial foundation and a complete industrial and supply chain, despite the uncertain external environment [1]. In the current era of high-quality development, China's industrial structure is gradually optimizing, and the modernization of its industrial chain continues to improve, with the manufacturing and modern service industries serving as the twin engines of growth. Under the ongoing COVID-19 pandemic, China must strive to maintain its stable position in the global industrial and supply chain, attract high-quality investment, strengthen industrial clusters, and adopt sustainable development policies for the industrial structure [2–4]. The path of China's industrialization will have a profound impact on its own economic development and that of the world as a whole, given the upstream and downstream linkages of its industries.

Over the past decade, China has witnessed rapid growth in its tertiary industry, which has served as the largest driving force for the country's economic development for six successive years. Specifically, between 2013 and 2021, the added value of the tertiary industry averaged an annual growth rate of 7.4%, 0.8 percentage points higher than that of the gross domestic product (GDP). Correspondingly, the average annual contribution of the tertiary sector to economic growth reached 55.6%, surpassing that of the secondary sector by 16.4 percentage points. Notably, in 2021, the added value of the tertiary industry accounted for 53.3% of the GDP, representing an increase of 7.8 percentage points compared to 2012, indicating a steady growth trajectory. Furthermore, in 2021, the investment in the tertiary industry reached 5624.7 billion USD, a 2.1% increase from the previous year, and the three industrial structures witnessed an adjustment from 9.1:45.4:45.5 in 2012 to 7.3:39.4:53.3 in 2021.

Both industrial rationalization and upgrading can lead to reductions in total electricity consumption, but it is worth exploring further whether there is regional heterogeneity in this effect and whether it will widen the gap in electricity intensity between Chinese provinces and industries.

1.2. Electricity and High-Quality Development

Since China's reform and opening up in 1978, the country's electrification level has steadily increased in tandem with its economic growth. The electric power industry has experienced tremendous development, transitioning from lagging behind to surpassing global benchmarks within a 40-year period. Proving its exceptional performance, China has been the world's largest producer and consumer of electrical power since 2011. Since 1978, the country's total power generation has soared from 257 billion kWh to 7327 billion kWh in 2019, marking a 27.5-fold increase. Moreover, per capita power generation has ascended from 268 kWh to 5233 kWh, representing an 18.5-fold increase [5]. Over the past two decades, China has experienced a significant rise in electricity consumption due to the improvement of industrialization, rapid economic growth, and enhanced living standards, resulting in a 9.8% annual growth rate in total electricity consumption between 1999 and 2018 [6].

China is the world's largest emitter of carbon dioxide, and electricity generation is based to a large extent on fossil fuels [7]. Electrification, meanwhile, refers to supporting the construction of new energy systems and building new power systems. As China strives to achieve its carbon peak, the development of electrification has been a crucial factor in successfully attaining sustainability targets [8]. Notably, China's electrification development level continues to rise while the proportion of electricity in terminal energy consumption consistently increases. In 2021, China's total social electricity consumption reached 8312.8 billion kWh, translating to a year-on-year growth rate of 10.3%, indicating a 14.7% hike when compared to figures from 2019. Regarding industrial power consumption, the primary industry consumed 102.3 billion kWh, marking a 16.4% increase from the preceding year. Concurrently, the secondary industry consumed 5613.1 billion kWh, recording a 9.1% increase. The tertiary industry consumed 1423.1 billion kWh, signifying a 17.8% rise, while the urban and rural residents' domestic electricity consumption amounted to 1174.3 billion kWh, indicating a 7.3% increase.

Using structural equation modeling, the study now shows that electricity consumption is an important driver of economic growth and that increased ecological awareness resulting from economic growth further strengthens the demand for clean energy generation. Electricity consumption helps promote clean energy substitution and carbon reduction, especially as China is currently undergoing industrialization and urbanization, where demand for electricity will remain high [5]. Applying joint cointegration tests and the autoregressive distributed lag (ARDL) method, the empirical analysis shows a long-term positive correlation between China's hydropower consumption and economic growth, with a bi-directional positive impact between hydropower consumption growth and economic growth based on the vector error correction model (VECM) Granger causality method [9]. The paper also shows that there is a long-run cointegration relationship between real GDP and social electricity consumption in China, and there is a one-way Granger causality between electricity consumption and real GDP [10]. The author highlights that China's economic development has depended on power input to a certain extent since the 1980s, presenting the possibility of strong future dependence [11]. Green development of the power sector plays a vital role in ensuring a reliable power supply, adjusting the energy structure, increasing energy efficiency, and reducing pollution [12]. Addressing the influence of the power substitution policy, this study concludes that the electricity sector can lead to economic output stimulation; promoting renewable energy consumption in the electricity sector contributes to sustainable economic growth, while the power substitution policy can contribute to China's green economic development [13].

In September 2020, China pledged to the global community its commitment to achieving a carbon peak by 2030 and carbon neutrality by 2060. According to the "Opinions of the Central Committee of the Communist Party of China and the State Council on Fully Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality", the government aims to replace its energy consumption with electric energy, making electricity consumption the primary source of energy consumption. By 2060, the consumption of electric energy will replace traditional energy sources in industries, transportation, construction, and other sectors. Presumably, the proportion of electrification in China's energy consumption will notably increase. In summary, to realize sustained economic growth and achieve China's "double-carbon" goal, promoting the proportion of electricity in energy consumption remains a priority for the country [14].

China is facing the challenge of uneven regional economic development, but the gap has been narrowing year by year. The issue of unbalanced regional economic development is not unique to China, as it is a common problem in many countries around the world [15]. The development pattern of the Chinese economy reflects this unevenness, with the southeast coast being the key area for trade and economic growth. The western region faces environmental, development, and investment limitations, while the central region has also experienced slower economic development compared to the southeast, which has more favorable conditions [16]. The study uses the entropy method to calculate the regional economic development imbalance index and finds that the imbalance has been decreasing from 2008 to 2017 [17]. The authors of the study focus on eight typical urban agglomerations in different regions of China and note that, while there are economic disparities among them, they are within a reasonable range. The authors suggest that a coordinated regional development strategy can help alleviate the imbalance [18].

Over the past decade, China has solidly promoted its regional development strategy, resulting in a new regional pattern and a narrowing of the economic gap. From 2013 to 2021, the gross domestic product of the eastern, central, western, and northeastern regions is expected to grow at average annual rates of 7%, 7.5%, 7.7%, and 4.7%, respectively. The central and western regions are developing faster than the eastern regions. In 2021, the per capita disposable income of residents in the eastern, central, western, and northeastern regions will be USD 6972, USD 4595.8, USD 4308.8, and USD 4730.4, respectively. The income ratio between the highest eastern region and the lowest western region has shrunk from 1.70:1 in 2013 to 1.62:1. The positive regional interaction has led to a gradual reduction in the relative gap.

China's energy consumption similarly shows regional imbalances. The level of urbanization affects energy consumption. Globally, urban energy consumption accounts for about 70% of total energy consumption since 2010 [19]. Household energy consumption in China differs among the three regions of eastern, central, and western. Moreover, the most important influencing factors of household energy consumption are different in all three regions [20,21]. China's energy consumption has increased by 3.5% compared to 2016. Furthermore, energy consumption in the eastern region is significantly higher than in other regions, and the gap is tending to widen [22]. The eastern provinces have high energy consumption, such as Shandong and Guangdong. There are significant differences in energy consumption between regions [23]. The distribution of residential energy consumption in China shows an "East-Middle-West" gradient pattern [24]. The growth rate of energy consumption in the eastern part of China is gradually decreasing. However, the western region is growing faster, with growth rates even exceeding those of the eastern region [25]. Using the Theil index and functional data analysis methods, the authors explored the differences in regional energy consumption in China. They found that the eastern region contributed the most to the overall difference in energy consumption. Additionally, the population factor is one of the most important influencing factors of energy consumption [23].

Reducing electricity intensity, minimizing electricity losses, and exploring a low-energy consumption development model for China to optimize its ability to serve the economy and society are among China's current priorities [26]. Therefore, it is worth investigating whether regional differences in energy intensity will narrow over time, leading to convergence. Analyzing the convergence process across regions is crucial because the finding of convergence may imply a diffusion of energy-related technologies across regions, and the differences may be a reason to alert the government to take further measures, especially in regions with low levels of energy efficiency.

1.3. Current Literature Review on Convergence

Convergence is an inevitable trend in economic development, and all economies will eventually converge in terms of output per capita [27]. Convergence analysis is currently used in numerous fields, such as carbon emissions, energy intensity, and energy efficiency. Club convergence is an important part of convergence analysis, interpreted as multiple steady-state paths when an economy reaches its steady-state path. Due to the prominent position of tackling climate change, many scholars have begun to study the convergence of energy intensity, energy productivity, and energy efficiency [28].

Current research has analyzed convergence at different sample levels. Most studies use quasi-metric and non-parametric methods to examine whether indicators converge across economies, countries, provinces, or sectors. Through log t regression, the paper examines the development trend of total factor carbon productivity in 88 economies and identifies potential convergence clubs. Although the whole sample does not show a convergence trend, there are five convergence clubs with significant differences in carbon productivity growth [29]. This paper studies the club convergence of total factor energy efficiency in countries along "The Belt and Road". The results show that the total factor energy efficiency of the countries along "The Belt and Road" appears to have a trend of differentiation and converges into three convergence clubs with different characteristics [30]. In addition, the convergence of energy efficiency under different sample levels of countries also includes Latin American countries [31], the European Union [32], and OECD countries [33]. The convergence of stochastic power intensity in Chinese provinces is studied. Due to the uneven distribution of energy resources in different regions, the study found that all regions will not form a unique club and will eventually form three clubs and a group. [34]. Convergence at the economic sector level has been widely discussed. The article notes that there is no club convergence for the emission intensity of the six major industries in all provinces. The convergence level of emission intensity of various sectors in China is determined using the club convergence identification algorithm [35]. Additionally, club convergence can also be discussed at the municipal sample level. Based on per capita energy consumption data from 243 prefecture-level cities in China, this paper uses a nonlinear time-varying factor model and clustering algorithm to test the club convergence effect of urban per capita energy consumption. The results show four convergence clubs and one divergence club [36]. Their results support the existence of group convergence, rather than convergence at the full sample level.

In recent years, the concept of club convergence has been used to conduct empirical studies on the influencing factors of energy structure upgrading. The article notes that China's foreign direct investment in low-carbon industries of countries along "The Belt and Road" is conducive to the convergence of clubs with high energy efficiency and high convergence rates [30]. The article found four convergence clubs in 193 cities, which showed significant differences in energy intensity. The orderly Probit model is used to conclude that the degree of marketization, population density, foreign direct investment, resource endowment, and industrial structure are driving factors for the formation of convergence clubs [37]. Empirical results show that there is no uniform convergence of renewable energy in EU countries. However, agricultural added value, foreign direct investment, open trade, land, information and communication technology, population, and institutional quality promote the possibility of forming a final convergence club [38]. The current aspiration of developed countries is not only to increase the share of renewable energy but also to reduce energy consumption to improve energy efficiency and break the long-term relationship between economic growth and growth in electricity consumption. In this context, it is more important to explore low-energy consumption development models.

Moreover, recent literature has highlighted the policy implications of club convergence. The author clearly points out that understanding the convergence mode of energy intensity and its driving factors is of great significance for local governments to implement targeted energy-saving policies [37,39]. The article points out that the development of green finance in China presents a phenomenon of club convergence. At the same time, it reveals the evolution trend and reasons for the green finance development gap. It provides a policy basis for promoting the coordinated development of green finance in China [40].

There are two problems with the current research on energy convergence. The first is that most of the existing literature has studied energy intensity, ignoring the relationship between China's electrification process and its coordinated economic development. Therefore, the study of electricity intensity convergence has practical implications for regional differences in China's electricity development and for exploring low-energy consumption development models. Secondly, the current sample level of research is focused on the national, provincial, and city levels, without further exploring the relationship between industries, ignoring the industrial restructuring that has taken place in China in recent years.

Therefore, considering that electricity intensity reflects the output value brought by kWh consumption, the trend of electricity intensity in each province of China reflects the efficiency of economic development to a certain extent. The key issues that this paper attempts to analyze are (1) to analyze the characteristics of regional industrial development by analyzing the development trend of inter-regional electricity intensity; (2) to explore the characteristics of development efficiency and trends among different industries in China by analyzing from three perspectives of GDP electricity intensity, secondary industry, and tertiary industry electricity intensity; (3) to provide policy recommendations for China's regional economic development based on these analyses of reference. Accordingly, the innovative points of this study could be concluded in three points. (1) Electricity intensity reflects the output value per unit of electricity, which is an important indicator reflecting the coordination between regional economy and energy consumption as well as high-quality economic development. (2) The club convergence log *t*-test used in this paper is a data-driven trend analysis method, which can reduce the subjective bias caused by artificial groupings and better reflects the real development and convergence tendency. (3) The results of the study state the regional diversity in electricity intensity, which implies the problems of imbalance during the industrialization of developing countries and provides insight for policymakers.

The paper is organized as follows: The first part is the background and introduction, the second part is the methodology and data, the third part is the empirical results and analysis, and the fourth part is the conclusion and corresponding policy recommendations.

2. Methodology and Data

Data-driven refers to the use of data as the central basis for decision-making and action. Data-driven scientometrics attempts to discover the latest developments and possible future research trends in a discipline by collecting a large amount of relevant information on a particular field or aspect of the discipline. It helps researchers understand the full picture of a field of study. Additionally, a data-driven approach can help scholars refine their research and further refine the empirical evidence of their papers based on methods such as statistical models, reliability functions, or artificial intelligence models [41]. Based on this, this paper selects electricity intensity data from 1997 to 2020 and runs log *t*-tests and club clustering algorithms for convergence analysis.

2.1. β-Convergence

Convergence refers to the negative correlation between the initial static indicators (e.g., output per capita, total factor productivity, electricity intensity, etc.) of different countries or regions and their regional economic growth rates. The main convergence test measures the β-convergence coefficients of region-specific indicators. β-convergence can be divided into absolute β-convergence and conditional β-convergence. For the power intensity convergence analysis, absolute β-convergence means that the growth of power intensity in all regions will eventually reach the same steady-state growth rate and growth level. Each economy converges to the same steady state. Conditional β-convergence takes into account the individual characteristics of different regions and states that eventually each economy converges toward its own steady-state level. Absolute β-convergence is a necessary but not sufficient condition for convergence. In the β-convergence test, the average growth rate of electricity intensity over time is regressed at its initial level. If there is absolute convergence, the coefficient at the initial level is negative and statistically significant [42]. The test equation for absolute beta convergence takes the form of:

$$ei\_rate_{it,i+T} = \alpha + \beta \ln(ei_{it}) + \mu_{it} \tag{1}$$

where ei_{it} it denotes the electricity intensity of province i in year t. μ_{it} is the random disturbance term. α and β are constant terms. $\beta < 0$ indicates the existence of absolute β-convergence. A smaller β indicates stronger convergence. $ei\_rate_{it,i+T}$ denotes average annual growth rate of electricity intensity from year t to year $t + T$. Its expression is shown below:

$$ei\_rate_{it,i+T} = \frac{\ln\left(\frac{ei_{it,i+T}}{ei_{it}}\right)}{T} \tag{2}$$

2.2. Club Convergence

Currently, many methods have been developed to study whether there is convergence in energy intensity in the sample. The traditional convergence test method has some shortcomings. The β-convergence test ignores variables and has endogenous problems. When there is transitional heterogeneity, the regression model will have bias. Moreover, in the cointegration test, due to the existence of the unit root of the series, there will be a phenomenon where the asymptotic co-movement cannot be identified [43]. The club convergence tests used in previous studies are usually divided into subgroups based on prior information such as geographical location and institutions. Then, the convergence of each subgroup is investigated separately. Therefore, there is a possibility of not identifying potential club convergence [29]. In view of the above shortcomings, Phillips and Sul proposed a nonlinear time-varying factor model, and showed a log t convergence regression test of simple regression. The model considered individual heterogeneity and possible time paths [44].

In the log t convergent regression test, panel data Y_{it} is usually decomposed into two components as follows.

$$Y_{it} = g_{it} + a_{it} \tag{3}$$

where g_{it} represents the systematic (permanent) component and a_{it} is the transitory component.

Because a mixture of the common component and the idiosyncratic component in two components may occur, transforming Equation (3) into the form of time-varying factors is conducive to separating the common component and the idiosyncratic component in the panel, namely:

$$Y_{it} = \left(\frac{g_{it} + a_{it}}{\omega_t}\right)\omega_t = \varepsilon_{it}\omega_t \tag{4}$$

where ω_t represents a common trend component, while ε_{it} is a special variable that varies with time. ε_{it} measures the special deviation between ω_t and systematic components Y_{it}. The formula is correct for all i and t. By using the above transformation, the question of convergence of Y_{it} is transformed into whether ε_{it} can gradually converge to a constant ε. To test convergence, construct a relative transition parameter:

$$h_{it} = \frac{Y_{it}}{N^{-1}\sum_{i=1}^{N} Y_{it}} = \frac{\varepsilon_{it}}{N^{-1}\sum_{i=1}^{N} \varepsilon_{it}} \tag{5}$$

where h_{it} measures the loading coefficient of ε_{it} relative to the panel average at time t. This indicator can measure the degree of deviation from the common trend component ω_t. The partial heterogeneity coefficient is expressed by the following semi-parametric equation:

$$\varepsilon_{it} = \varepsilon_i + \frac{\xi_i}{\mathrm{L}(t)t^{\alpha}} \times \eta_{it} \tag{6}$$

where $t \geq 1$, $\varepsilon_i > 0$. Among them, ε_i, as a fixed variable, represents the common characteristics of each region; η_{it}~iid (0,1); The function L(t) satisfies lim $t \to \infty$ L(t) = ∞. This improves the effectiveness of the testing. α represents the rate of convergence. If $\alpha \geq 0$, then it can be proven that ε_{it} converges to ε_i. The following hypothesis tests are derived.

Null hypothesis H0: $\sigma_i = \sigma$ and $\alpha \geq 0$.

Alternative hypothesis H1: $\sigma_i \neq \sigma$ or $\alpha < 0$ exists.

Null hypothesis means that all regions converge, while the alternative hypothesis means that some regions do not converge, indicating the possibility of local convergence to multiple equilibria. The hypothesis testing involves the following log t regression model:

$$\log\left(\frac{H_1}{H_t}\right) - 2\log\{\log(t)\} = b_0 + b\log t + \mu_t \tag{7}$$

where H_1 and H_t are function values. The function is represented as follows:

$$H_t = N^{-1}\sum_{i=1}^{N}(h_{it} - 1)^2 \tag{8}$$

where h_{it} is the relative transition parameter; b_0 is a constant term and $b_0 = -2\log\{\log(1)\} + \mu_1$; $t = [rT], [rT] + 1, [rT] + 2, \ldots, T$, with $r > 0$. The hypothesis test aims to verify whether panel data converges to Y_{it} through the log t regression model.

If the null hypothesis is rejected, the existence of club convergence should be explored through a series of log t regression processes.

Step 1. Sort all individuals in the panel data based on the last observation in the panel.

Step 2. Build core groups by selecting the first n highest individuals in the group to form a subgroup G_n with $N > n \geq 2$. Run log t regression on the subgroup to calculate its convergence test statistic $t_n = t\ (G_n)$. Select the core group size n^* according to the following criteria:

$$n^* = argmax(t_n), s.t.min\{t_n\} > -1.65 \tag{9}$$

According to the HAC standard error criterion, at the 5% significance level, if $t < -1.65$, the null hypothesis of convergence is rejected. If there is no subgroup satisfying min $\{t_k\} > -1.65$, it is considered that there is no convergent subgroup.

Step 3. Select club members. Add individuals to the core subgroup G_n one by one, and run log t regression every time. Set the regression t statistic as t_c. If $t_c > c$, new individuals will join the subgroup to form the first sub convergence group. C is a manually selected critical value. All members in the group need to meet $t_c > -1.65$. If not, consider increasing the set value c.

Step 4. In step 3, individuals with $t_c < c$ form subgroup G_d, and log t test is conducted for this subgroup. If the regression t statistic $t_d > -1/65$, there are two convergent subgroups in the panel. If this is not the case, overlap steps 1, 2 and 3 to identify if there are smaller panel club convergence members. If there is no n in step 2 to make $t_n > -1.65$, it means that other individuals in the panel are divergent.

All analyses in this study were carried out by using Stata software. In particular, the club convergence analysis methodology used in the main research section was carried out using the guidelines published by Kerui Du in Stata Journal.

2.3. Variables and Data

The annual provincial variables from 1997 to 2020 of sectional and total electricity consumption are obtained from The National Energy Administration. Total electricity usage (e) is marked as *e_enduse*, and sectional electricity consumption for industry, construction, transportation, and services are marked as *e_ind*, *e_const*, *e_trans*, and *e_serv*. According to the statistical method in China, the sum of *e_ind* and *e_const* could be employed as the proxy electricity use for the secondary industry (*e_2nd*), while the sum of *e_trans* and *e_serv* could be applied as the proxy electricity use for the tertiary industry (*e_3rd*), as in Equations (10) and (11), where *it* denotes the province i in year t.

$$e\_2nd_{it} = e\_ind_{it} + e\_const_{it} \tag{10}$$

$$e\_3rd_{it} = e\_trans_{it} + e\_serv_{it} \tag{11}$$

By dividing the electricity consumption for each industry with the annual added value, which are marked as *GDP*, *ADDV2nd*, and *ADDV3rd*, which are quoted from the Statistical Yearbooks published by the National Bureau of Statistics of China, the core variables of *ei*, *ei_2nd*, and *ei_3rd* are obtained to identify the provincial electricity intensities for the total economic development, the secondary industry and the tertiary industry, as in Equations (12) to (14). According to the equations, the electricity intensity represents the electricity consumption for one unit of GDP added value in secondary industry and tertiary industry. In this way, a high electricity intensity denotes a relatively low energy efficiency. Descriptive statistics for the variables are listed in Table 1.

$$ei_{it} = \frac{e_{it}}{GDP_{it}} \tag{12}$$

$$ei\_2nd_{it} = \frac{e\_2nd_{it}}{ADDV2nd_{it}} \tag{13}$$

$$ei\_3rd_{it} = \frac{e\_3rd_{it}}{ADDV3rd_{it}} \tag{14}$$

Table 1. Statistical description of the raw data.

Variable	Mean	SD	Max	Min	N
e_enduse	124,563.200	120,488.400	696,509.000	498.000	715
e_ind	83,869.980	81,089.180	535,223.000	498.000	667
e_const	1618.005	1534.838	9722.000	35.000	713
e_trans	2671.455	2519.784	17,975.520	54.000	714
e_serv	4646.772	5577.146	42,806.000	29.000	712
ADDV2nd	4397.451	5048.128	28,923.920	61.700	720
ADDV3rd	4725.877	5806.745	40,305.670	91.100	720
GDP	10,057.140	11,255.060	71,622.420	202.800	720
ei	0.165	0.124	1.448	0.011	715
ei_2nd	0.312	0.326	4.921	0.087	665
ei_3rd	0.019	0.009	0.129	0.007	712

3. Empirical Results and Analysis

3.1. Test of β-Convergence

Prior to the club analysis, regression models were fitted using absolute β-convergence methods to assess the electricity intensity of the 30 provincial administrative regions and the electricity intensity of the secondary and tertiary sectors in China. A set of regression models based on Equations (1) and (2) were used to perform absolute β-convergence analysis for these three variables. If the estimated coefficients are negative and statistically significant, then absolute β-convergence can be considered to exist. As shown in Table 2, columns 2 to 4 show the results of the absolute beta convergence estimates for China's provincial electricity intensity, secondary sector electricity intensity, and tertiary sector electricity intensity, respectively. We note that the beta coefficients for these three variables are −0.346, −0.065, and −0.363, respectively, all of which are negative and statistically significant, providing support for the assumption of beta convergence. The results show that electricity intensity converges across provinces and industries. The rate of absolute convergence of electricity intensity in the secondary sector is the smallest, indicating a less pronounced convergence trend and a greater variation in the efficiency of electricity use in the secondary sector across Chinese provinces. Nevertheless, significant regional heterogeneity may still bias the results. To mitigate this potential variation, a log *t*-test was conducted and the CLUB clustering algorithm was applied.

Table 2. Test of β-convergence for electricity intensity in China' provinces.

	l_ln*ei*	**l_ln*ei_2nd***	**l_ln*ei_3rd***
Beta Coefficient	−0.346 ***	−0.065 ***	−0.363 ***

Notes: *** represents the significance level 1%.

3.2. Club Convergence Analysis

The following section empirically analyses the convergence hypotheses for GDP per kWh of electricity consumption of the secondary industry and the tertiary industry for 30 provincial-level administrative regions in China. The log t convergence regression test is conducted for all three sectors, which is used to analyze the convergence trend of the overall sample. The results of the analysis are shown in Table 3.

Table 3. Log t test for electricity intensity in China' provinces [1].

Variable [2]	**Log (t)**		
	ei [3]	***ei_2nd***	***ei_3rd***
$\hat{b}$	−1.730	−0.903	−0.769
SE	0.023	0.001	0.087
$t_{\hat{b}}$	−74.176	−1050.976	−8.857

[1] The number of individuals is 30, the number of time periods is 24. [2] The three variables in the variable column represent coefficient, standard error and t statistics, respectively. [3] *ei*, *ei_2nd*, and *ei_3rd* denote the electricity intensity of GDP, the electricity intensity of the secondary industry and the tertiary industry, respectively.

The results in Table 3 show that $t_{\hat{b}} < -1.65$ for all three electricity intensities of concern in this paper, indicating that the original hypothesis of convergence is rejected at the 5% level. Therefore, it can be concluded that no convergence in electricity intensity is observed across the Chinese provinces in the full sample. That is to say, at the national level, there is still a divergence in the electricity intensity of GDP, secondary industry, and tertiary industry across provinces. In order to further analyze this divergent trend, this paper uses a data-driven analysis approach to conduct further research, and a club convergence analysis is applied to explore the relative convergence within the full sample.

Table 4 shows the results of the data-driven analysis approach. Based on Table 4, the three power intensities of interest in this paper have club convergence, indicating that the relative convergence exists although the samples diverse from a general perspective. In Table 4, the first part shows that the power intensities of GDP for the 30 provinces initially converge to five clubs with $t_{\hat{b}} > -1.65$ for each club. In addition, there is Shanghai as the only provincial administrative region that does not converge to any club. This paper further used the club merging algorithm to try to merge neighboring clubs. However, according to the results of the analysis, there is no club with $t_{\hat{b}} < -1.65$ after the combination. As a result, the electricity intensity of GDP still eventually converges to the five clubs obtained from the initial analysis, with Shanghai city, which does not converge to any club. The absence of club convergence in Shanghai might be explained by the specific mode of development and urbanization in in Shanghai, which keeps its electricity intensity at a relatively low level [45], as is compared in Figure 1.

The second part of Table 4 shows the results of the analysis of the convergence of the secondary industry electricity intensity clubs. The secondary industry electricity intensity for the 30 provinces initially converged into seven clubs. The paper further uses the club merging algorithm to merge neighboring clubs. According to the principles of club merging, for new clubs, the criterion for merging two adjacent clubs must satisfy $t_{\hat{b}} > -1.65$. For indicator *ei_2nd*, merging clubs 4 and 5 yields a $t_{\hat{b}}$ of 1.251, which is greater than −1.65, indicating that clubs 4 and 5 in the initial club can be merged into a new club. The $t_{\hat{b}}$ corresponding to the results of the merging of the other clubs are all less than −1.65, so they do not proceed with further merging. Thus, the electricity intensity of the secondary industry eventually converges to six clubs. Details of the merging process and the corresponding t-statistics for the *ei_2nd* indicator is shown in Table 5. As can be seen from the table, only Club 4 + 5 satisfies $t_{\hat{b}} > -1.65$; therefore, the study only considers the merger of Clubs 4 and 5 to form a new club.

Table 4. Classification by testing of club convergence.

ei	Club 1	Club 2	Club 3	Club 4	Club 5	Not Convergent	
$\hat{b}$	−1.5	−0.821	0.077	1.911	0.339		
$t_{\hat{b}}$	−0.399	−1.033	1.639	14.389	1.512		
Number of provinces	2	3	17	3	4	1	
ei_2nd **Initial Club**	**Club 1**	**Club 2**	**Club 3**	**Club 4**	**Club 5**	**Club 6**	**Club 7**
$\hat{b}$	−0.077	−3.384	−0.054	3.056	0.716	0.797	−2.242
$t_{\hat{b}}$	−0.482	−0.914	−1.272	7.526	1.368	2.290	−54.441
Number of provinces	2	2	12	6	2	3	3
Final Club	**Club 1**	**Club 2**	**Club 3**	**New Club 4 = Club 4 + 5**		**Club 5**	**Club 6**
$t_{\hat{b}}$	−0.482	−0.914	−1.272	1.251		2.290	−54.441
Number of provinces	2	2	12	8		3	3
ei_3rd	**Club 1**	**Club 2**					
$\hat{b}$	0.009	0.229					
$t_{\hat{b}}$	0.225	2.382					
Number of provinces	19	11					

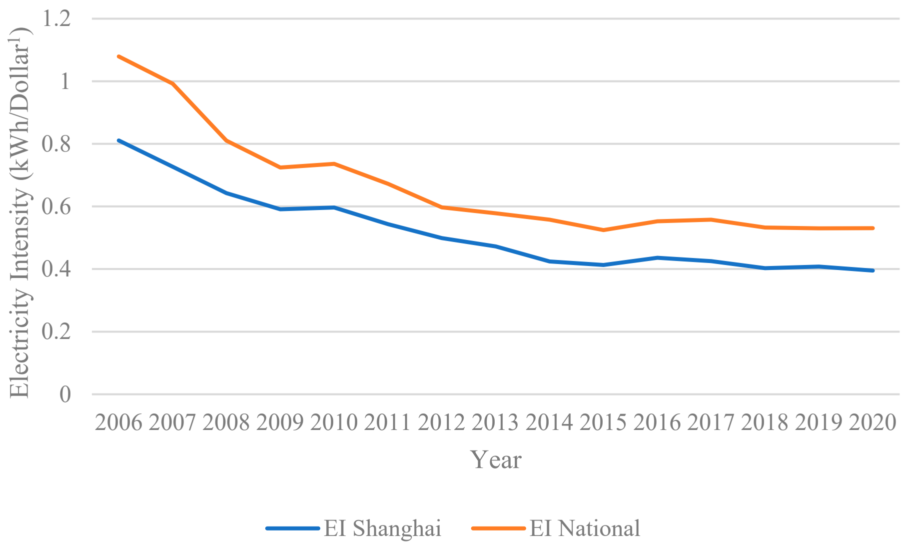


Figure 1. The electricity intensities of GDP for Shanghai and national average level. [1] GDP in the graph is the real value based on 1997, converted to U.S. dollars through the annual exchange rate of the China Foreign Exchange System.

Table 5. Estimated results of club merging for *ei_2nd* indicator.

Log (t)	Club 1 + 2	Club 2 + 3	Club 3 + 4	Club 4 + 5	Club 5 + 6	Club 6 + 7
$\hat{b}$	−1.237	−1.281	−0.578	1.251	−0.69	−1.201
$t_{\hat{b}}$	−7.528	−15.744	−32.789	8.08	−3.046	−86.549

The third part of Table 4 shows the results of the analysis of the convergence of the tertiary industry electricity intensity clubs. The results show that the tertiary industry electricity intensity for the 30 provinces initially converged to two clubs with $t_{\hat{b}} > -1.65$ for each club. The paper further merged neighboring clubs using the club merging algorithm. However, according to the results of the analysis, no club after merger has $t_{\hat{b}} < -1.65$. Therefore, the tertiary industry electricity intensity still eventually converges to the two clubs derived from the initial analysis.

There is a significant difference in the number of converging clubs between the electricity intensity of the secondary industry and the electricity intensity of the tertiary industry.

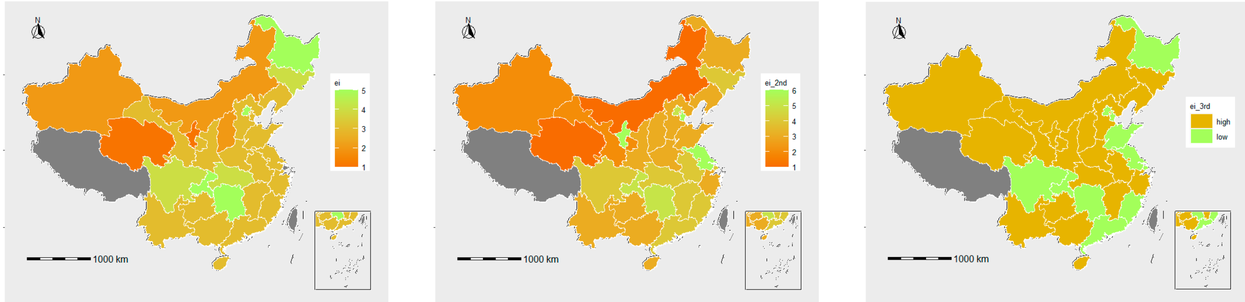
This reflects the fact that there are significant differences in the efficiency of electricity use in the secondary sector (industry and construction) across China's provinces, but these differences are converging. In contrast, there is relatively little disparity in the efficiency of electricity use in the tertiary sector (transport and services) across China's provinces, either because the demand for electricity in these sectors is relatively low, or because these sectors use electricity in a relatively more regulated manner.

The categorization of the final clubs is shown in Table 6. To provide an easy understanding of their geographical distribution and to facilitate comparison of the convergence trends of the three electricity intensities, the study further plotted a map of China based on the results of Table 6, as shown in Figure 2. As shown in Table 6, the club convergence analysis when applied to GDP electricity intensity, the converging subgroup consists of five clubs as well as the presence of a non-converging cluster. The converging subgroup for the electricity intensity of the secondary sector consists of six clubs. The converging subgroups of tertiary sector power intensity consist of just two clubs.

Table 6. Final clubs and club convergence of provinces.

	Provinces
ei	
Club 1	Qinghai, Ningxia
Club 2	Shanxi, Inner Mongolia, Xinjiang
Club 3	Tianjin, Hebei, Liaoning, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Shaanxi, Gansu
Club 4	Jilin, Hubei, Sichuan
Club 5	Beijing, Heilongjiang, Hunan, Chongqing
Not convergent	Shanghai
ei_2nd	
Club 1	Inner Mongolia, Qinghai
Club 2	Gansu, Xinjiang
Club 3	Hebei, Shanxi, Liaoning, Heilongjiang, Zhejiang, Shandong, Henan, Guangxi, Hainan, Guizhou, Yunnan, Shaanxi
Club 4	Jilin, Anhui, Jiangxi, Hubei, Guangdong, Sichuan, Shanghai, Fujian
Club 5	Beijing, Hunan, Chongqing
Club 6	Tianjin, Jiangsu, Ningxia
ei_3rd	
Club 1	Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Zhejiang, Anhui, Jiangxi, Henan, Hubei, Guangxi, Hainan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Club 2	Beijing, Tianjin, Heilongjiang, Shanghai, Jiangsu, Fujian, Shandong, Hunan, Guangdong, Sichuan, Chongqing

From Figure 2, the similarity of club distribution between electricity intensity of GDP and secondary industry could be witnessed in Figure 2a,b in which Qinghai, Inner Mongolia, and Xinjiang are classified as highly intended regions in electricity consumption. Considering that China is at the stage of industrial development, the overall energy intensity and the energy intensity of the secondary sector are relatively close in trend. In terms of geographical distribution, most of the provinces in the northern and western regions are classified in the higher intensity clubs, which also means that energy intensity control in these regions is more noteworthy. In contrast, the provinces in the central and eastern regions are mostly classified in the lower intensity clubs, implying a more favorable trend in these regions. The trend in energy intensity in the tertiary sector in Figure 2c shows a divergence in the national sample, with those located in the south–east showing a positive trend, while other regions still show higher energy intensity.



(**a**) GDP (**b**) Secondary industry (**c**) Tertiary industry

Figure 2. The final clubs of the electricity intensities for sectors. Note: Provincial-level administrations not included in the sample are marked in grey.

Figure 3 further depicts, from left to right, the final geographical distribution of each club based on the three indicators of GDP electricity intensity, secondary sector electricity intensity and tertiary sector electricity intensity. The results in the figure show that, first, the trends in the two indicators of GDP electricity intensity and secondary sector electricity intensity show that the main constituent provinces of the high electricity intensity clubs (high-*ei* clubs) are more often from the western region (e.g., Club 1 and Club 2 corresponding to *ei* and *ei_2nd*). Similarly, the eastern provinces are more densely distributed in the medium-intensity clubs (mid-*ei* clubs), while the central provinces are mainly distributed in the medium-low electricity intensity clubs (midlow-*ei* clubs).

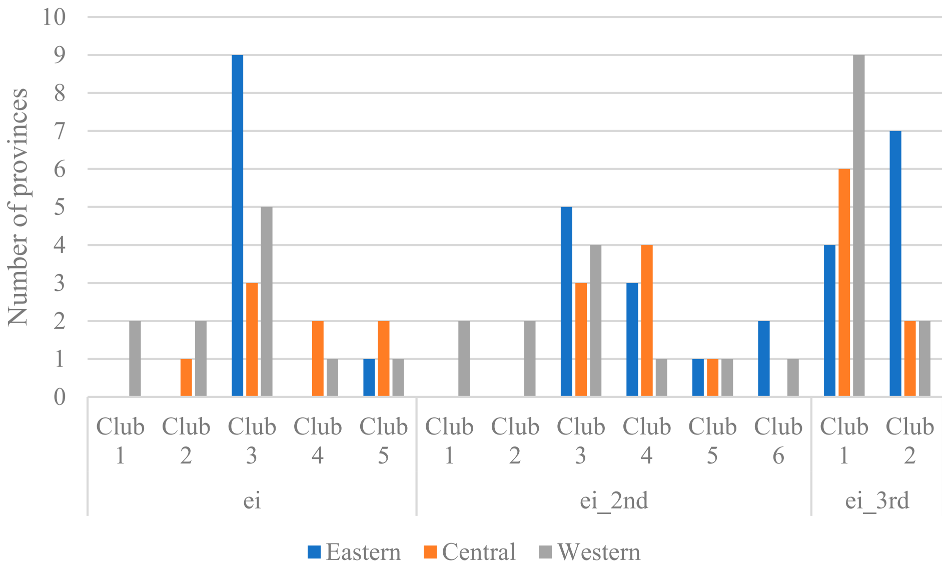


Figure 3. Numbers of provinces in final clubs.

3.3. Discusstion: The Trend and Distribution

Figure 4 depicts the evolution of GDP electricity intensity by province over time. The figure shows that from 1997 to 2020, the high electricity intensity provinces located in Club 1 show an upward to downward trend in electricity intensity, this is largely attributable to a range of energy consumption control measures in China. While the provinces in Club 2 are noted to remain at relatively high levels. In contrast, Clubs 3 to 5 remain at a lower and flatter level. It is also worth noting that most of the provinces with higher electricity intensity are located in the west, and the paper goes on to further explain the east–west differences.

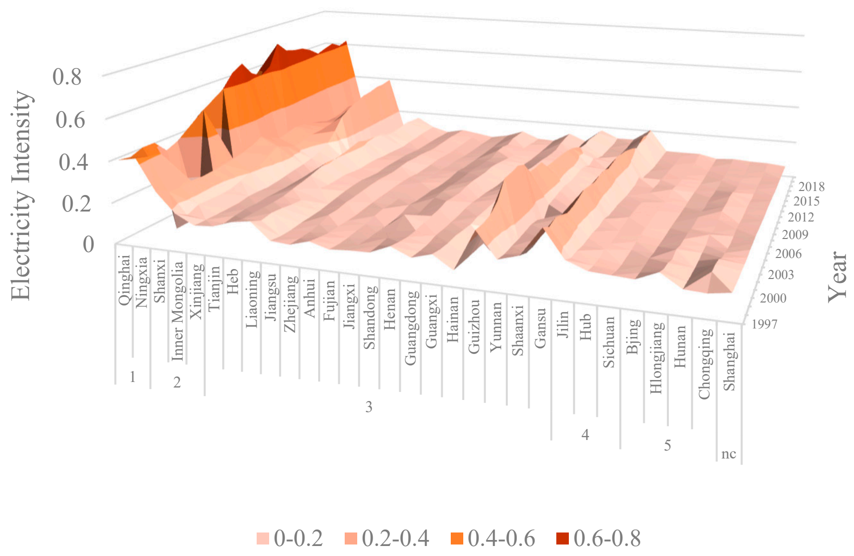


Figure 4. The trends of electricity intensity of GDP for provinces in different clubs. Notes: a. Considering that official exchange rate is started from 2006, the electricity intensity is calculated in Chinese Yuan and the unit for the intensity is kWh/CNY. b. The numbers from 1 to 5 under the names of provinces represents the final clubs of GDP electricity intensity; nc means Shanghai city does not convergent to any of the clubs.

First, most of the provinces with higher electricity intensity are located in the west due to the advantages of abundant energy resources and relatively low labor costs in the region. Additionally, the NIMBY effect in the east has led to the gradual shift of high energy-consuming industries to the west. The rise of high energy-consuming industries in Shanxi, Shaanxi, Inner Mongolia, and Ningxia was the inevitable result of industrial restructuring in the 1990s, and these industries have developed rapidly in the western region. There is a clear industrial gradient between the eastern and western regions of China, laying the foundation for industrial transfer. China's abundant energy resources are mainly located in the west, where there is vast space for economic development, abundant resources, and relatively low labor costs. In recent years, traditional industries have been gradually shifting to the west as industrial transformation and upgrading accelerate in the east. The NIMBY effect has contributed to this trend by directing opposition to projects such as waste-to-energy plants, chemical plants, and power transmission lines, particularly in the eastern and central regions of Beijing, Hangzhou, Nanjing, and Haikou [46]. In contrast, this opposition was not widespread in the western regions, further contributing to the development of energy-intensive industries.

Second, the electricity intensity in the central provinces is mainly at a low to medium level. This is a result of the Chinese government's ongoing strategy to revitalize the old industrial bases in the northeast and promote the rise of the central region. The strategic rise of the central region involves Shanghai's leading role in the integration of the Yangtze River basin, as well as the development of national central cities such as Wuhan and Zhengzhou, and the increased radiation-driven capacity of regional central cities such as Changsha, Hefei, Nanchang, and Taiyuan. Additionally, Anhui Province has received support in actively integrating into the integrated development of the Yangtze River Delta and building an emerging industrial hub with significant influence. Driven by national strategies, the central provinces are gradually becoming one of the key engines of China's economic development, with a constantly optimized industrial structure.

Third, we have identified some overlap in the low electricity intensity club (low-*ei* club) for both provincial electricity intensity and secondary sector electricity intensity with provincial administrative areas, such as Beijing, Hunan, and Chongqing. These areas are all located in the final Club 5 corresponding to these two indicators. Shanghai's low electricity intensity is due to its advanced industrial structure. Currently, Shanghai has developed a strategic emerging industry system led by nine strategic emerging industries. The tertiary industry dominates Shanghai's industrial structure and is supplemented by the secondary industry. This is also the case in Beijing, where the share of tertiary industries reached 81.7% in 2021, while the share of secondary industries was only 18.0%. Due to its status as the capital, Beijing's energy-intensive industries have significantly reduced as many general manufacturing and polluting enterprises have exited the city. Hunan's low electricity intensity is mainly due to the over-optimization of its industrial structure. During the "12th Five-Year Plan period", Hunan's energy consumption per unit of industrial value added fell by a cumulative 46.2% over five years, far exceeding the target of 18% energy saving.

Finally, the intensity of electricity consumption in the tertiary industry is more convergent across China's provinces and is strongly correlated with the level of regional economic development. We found that the electricity intensity of the tertiary industry showed more convergence across the 30 provinces of the country compared to the secondary sector. This is because the results of the club analysis of electricity intensity in the tertiary sector are divided into only two clubs. Furthermore, electricity intensity reflects the value of electricity output in kWh. Therefore, the regional provincial distribution of the two clubs indicates that the electricity output of the tertiary sector is higher in the eastern region, while it is relatively lower in the western region. In terms of the level of economic development, the top seven provinces in terms of GDP in the first half of 2022, with the exception of Henan Province, belong to the low intensity club (low-*ei* club) for electricity consumption in the tertiary sector. This indicates a strong correlation between the intensity of electricity in the tertiary industry and the level of regional economic development.

Our paper shows that there is club convergence in electricity intensity among provinces and industries in China. In contrast to previous studies, we use energy intensity data for 30 Chinese provinces from 2000 to 2015 and find that there is no σ-convergence across provinces, and the energy intensity gap is increasing [47]. Our results suggest that it would be more reasonable for China's provinces to set refined targets for the development of the electricity industry in the "13th Five-Year Plan" period, which would help reduce the gap between provinces and decrease electricity losses. Additionally, we find that the geographical distribution of convergence clubs is relatively clear, and the pattern of low-energy consumption is closely related to the geographical location of provinces, regional radiation capacity, and industrial structure. This finding is consistent with previous studies and supports the validity of our findings. We developed a spatial Durbin panel model, and the results show that regional energy intensity is low in the southeast and high in the northwest, with β-convergence. Economic development can contribute to the convergence of regional energy intensities [48].

4. Conclusions

In recent years, China has optimized its industrialization structure and increased its level of electrification. Reducing electricity intensity and power losses is currently a topic of concern. Using a data-driven approach, this paper collects data on the electricity intensity of Chinese provinces and studies the convergence of energy intensity. We also use a statistical model to investigate whether the long-term trend of electricity intensity converges between Chinese provinces and industries.

This study examines the existence of club convergence in GDP electricity intensity, secondary industry, and tertiary industry in 30 provincial administrative regions of China using the club clustering algorithm developed by Phillips and Sul. The empirical results show that: (1) the geographical distribution of the clubs is relatively clear. The main constituent provinces of the high electricity intensity club are mostly from the western region; the eastern provinces are more densely distributed in the medium intensity club, while the central provinces are mainly distributed in the medium and low electricity intensity club; (2) the low intensity of GDP electricity intensity and secondary industry electricity intensity have some overlap with provincial administrative regions, such as Beijing, Hunan, and Chongqing; (3) the electricity intensity of the tertiary industry convergence is stronger compared to that of the secondary industry. The power intensity of the tertiary industry is higher in the eastern region, while it is relatively lower in the western region. Additionally, the value-added of electricity in the tertiary industry is more closely correlated with the regional economic development level. Compared to previous studies, this further validates our findings and highlights the importance of provincial governments refining their energy development goals.

Power intensity measures the output value of electricity per unit and objectively reflects the degree of utilization of electrical energy by economic activities. It is an important indicator of the coordination between regional economy and electricity consumption and a measure of high-quality economic development. It is a better indicator of regional economic trends than a single energy intensity. During the "14th Five-Year Plan" period, China's economic development has entered a new era of high-quality development, and the industrial structure has been further transformed and upgraded. The proportion of primary industry has been steadily declining, but due to the implementation of strategies such as rural revitalization, the proportion of primary industry will drop slightly to about 6.5%. In the context of new science and technology and industrial change, new energy technology development, "double carbon" target, China's industrial innovation and development capacity has increased significantly, and the green development trend driven by high-end technology has gradually emerged. In the context of industrial transformation and upgrading, green development, the development of China's tertiary industry ushers in new opportunities, and the advantages of emerging industries are prominent. The proportion of tertiary industry is expected to increase and has good convergence. Given this, it is sensible to discuss China's low-energy model for development.

Due to inherent regional differences, general policies for energy and industrial development may not be appropriate. Instead, regional policies should be developed, taking into account factors such as geographical location, regional radiative capacity, and the current state of the industrial structure. By considering these aspects, we can design appropriate low-energy development policies for energy and industry for different regions.

This paper provides insights into the study of low-energy development patterns in China, exploring whether provincial electricity intensities and differences in electricity intensity between industries will achieve convergence. However, we also acknowledge that there are some limitations to this study and much work remains to be done. First, there is a lack of exploration of the potential drivers of convergence club formation. Further research could deepen the understanding of convergence. Second, the omission of spatial spillover effects may underestimate convergence. Finally, the reality is that the structure of energy consumption is also an important factor influencing the electricity intensity of provinces, which is not reflected in the paper's findings.

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